

# STRATEGIES FOR THE SEARCH OF LIFE IN THE UNIVERSE

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## 1. Introduction

The question of the existence of Life elsewhere in the Universe is probably the oldest scientific question since it was already formulated in appropriate terms by Epicurus in his ‘Letter to Herodotus’ [11]. Today, particularly with the opportunities opened by space missions, this perspective is becoming a scientific reasonable goal. Nevertheless one prerequisite is to have an idea of what we want to search for, i.e. an idea of what we mean by ‘Life’. In order to miss the fewest conceivable forms of Life, we should start with as few *a priori* assumptions as possible. Let us briefly sketch an argumentation in 6 steps:

1. Contrary to what is usually claimed by biologists, the very essence of Life is a subjective notion. ‘Life’ is, at first, only recognized as such on *a priori subjective* grounds. The everyone’s experience shows the importance of a privileged criterion: richness of subjective exchanges with *us*.
2. It is only in a second step that the physical analysis of a system judged as living exhibits an essential attribute: it has rich physical exchanges with its surrounding, implying that its structure is sufficiently complex. Physically speaking, a complex system is an out of thermodynamical equilibrium system.
3. Out of equilibrium systems can spontaneously acquire a complex structure only after a long natural process of self-complexification (amplification of instabilities). In biological terms, this means *Evolution*. This requires a *permanent source of high neguentropy*.
4. Because of the second law of thermodynamics, a complex system is unstable. Thus there must be a continuous *regeneration* mechanism which maintains the complex structure. This mechanism necessarily requires

*exchanges* of matter and energy with the *surrounding*. In biological terms, this means alimentation and photosynthesis

5. If alimentation is not sufficient, there is another mechanism named *reproduction*. On the Earth, we know two such reproduction mechanisms: mitosis and sexual reproduction.
6. Another reasonable requirement is that, in order to minimize the expenses in energy, the structure of the system should be as stable as possible, or its evolution as steady as possible. This is well implemented by some kind of *memory*, together with a reading mechanism. The genetic code is a good example of such a memory. On the other hand, the stability of the systems also requires the *stability of the environment*.

The above requirements are too general to serve as guidelines for actual searches of Life outside the solar system. We need more specific hypotheses.

1. What kind of complex system? There are several possibilities:

- (a) chemical (organic) systems
- (b) electromagnetic plasmas
- (c) solid state physics
- (d) liquid electronics, liquid crystals ....
- (e) others ? ...

A standard conservative choice is to restrict the search to chemical systems. We can then specify further more restricting hypotheses:

2. Consider only *carbon-based organic chemistry*
3. Require the presence of *liquid(s)*: favors the convective and hydrodynamical mixing of molecules
4. The liquid must be *water*: it is a very good dissolvent and is abundant in nature.
5. Require the existence of a *solid/liquid interface* to enhance the exchanges between molecules.

From the above ‘decision tree’, the safest environment which our imagination has yet found is an ‘habitable’ planet. It is a planet having the following characteristics:

- It is in orbit around a ‘main sequence’ star (i.e. a star burning steadily its light elements into heavy elements) for its source of out-of-equilibrium photons.
- It must be a solid planet to allow for a liquid-solid interface; this excludes (giant) gaseous planets of the Jupiter type.
- It is at the right distance from the star to allow for liquid water. A planet orbiting at a distance  $a$  around a star with a radius  $R_*$  and a temperature

$T_*$  acquires, by heating an equilibrium temperature  $T_P$  given by

$$T_P = \frac{(1 - A)^{1/4}}{\sqrt{2}} \left( \frac{R_*}{a} \right)^{1/2} T_* \quad (1)$$

where  $A$  is the mean ‘albedo’ (reflectance) of the planet surface. For instance, by Eq. (1), the equilibrium temperature of the Earth ( $A = .39$ ), heated by the Sun ( $T_\odot = 5770K$ ), is

$$T_\oplus = 280K$$

(the actual mean temperature of the Earth’s atmosphere is 287 K).

Thus, from Eq. (1), a planet having a temperature  $\simeq 300 \pm 20K$  (to allow for liquid water) must be located at a distance  $a$  from the star given by (for  $A = 1$ ):

$$a = R_* \left( \frac{T_*}{300} \right)^2 \quad (2)$$

Depending on the type of the central star, this distance runs from  $\simeq 0.1$  AU for cool ( $T_* = 3000K$ ) dwarf stars to  $\simeq 2$  AU for hot ( $T_* = 6500K$ ) larger stars (1 AU, or Astronomical Unit is the Sun-Earth distance). Hoter stars evolve too rapidly to have stable temperature conditions.

## 2. Detection of habitable planets: what it is conceivable to do.

The potential success of a given detection method depends naturally on its technological limitations, but also on the different characteristics of the planets: their mass  $M$ , radius  $R$  and distance  $a$  from the parent star (I assume circular orbits).

### 2.1. THE OBSERVABLES IN EACH DETECTION METHOD.

Consider a planetary system at a distance  $D$  from the solar system with a planet at a distance  $a$  from its ‘parent’ star. There are several methods to detect the planet either directly or indirectly.

1. The most straightforward idea is to take a picture of the planet. Unfortunately it is at a very small angular distance  $\Delta\theta = a/D$  from the star and is, by illumination by the star, very faint (the planet to star brightness ratio  $I_P/I_* = (1/4)(R_P/a)^2$  is only  $\simeq 10^{-9} - 10^{-10}$ ). Its image is therefore blurred by the star’s halo due to the diffraction and diffusion of light in the telescope.
2. A second series of methods rests on the detection of the ‘reflex’ motion of the star due to the gravitational influence of the planet: the star

goes, with a period equal to the period  $P$  of orbital revolution of the planet, over an orbit with a radius  $(M_P/M_*) \times a$  around the center of mass of the planet-star system. The star's motion can be detected by three means:

- (a) Modulation of the star's position on the sky: its apparent trajectory is the elliptic projection of its orbit and has an angular amplitude  $\Delta\alpha = (M_P/M_*)(a/D)$ .
  - (b) Measurement of the star's velocity: by application of the Kepler laws, the velocity of the star is modulated with a period  $P$  and an amplitude  $V_R = (M_P/M_*)\sqrt{GM_*/a}$ , where  $G$  is the Newton constant of gravity.
  - (c) Variation of the star's distance to the observer. Suppose there is some emission mechanism on the star, sending periodic signals to the observer. When the star moves, the observer will receive the signals with a (positive or negative) delay with respect to their mean time of arrival because of the variation of length of the star-observer distance. This delay will be modulated with a period  $P$  and an amplitude  $\Delta T = (M_P/M_*)(a/c)$ , where  $c$  is the speed of light. In actual situations, the star can be a pulsar and the periodic signal the pulse of the pulsar.
3. If the star has modulations in its light curve (flares etc.), the planet presents, by illumination, the same modulations with a delay  $DT$  and a relative amplitude  $R^2/a^2$ . An autocorrelation study of the star light curve could reveal this echo [3].
  4. If the orbital plane of the planet is correctly oriented, it produces a drop  $\eta$  in the star light during transits (duration  $D_{occ} \approx 1\text{-}20\text{hrs}$ ); for a random orientation of the planet orbital plane, the geometric probability of the transit is  $p = R_*/a$  for a single star; for an eclipsing binary this probability can amount 100% since it is likely that the binary and planet orbital planes are identical; in the latter case the transit is double ([19]).
  5. The planet can produce a gravitationnal amplification  $A_G$  of the light of background stars with a duration  $T_G$  depending on its transverse velocity  $V$  [15].
  6. Finally the planet can, like Jupiter or Saturn, have an intrinsic radio emission with a flux  $F_R$  and could be searched by this emission [12]. At the present knowledge, the latter is possible for any kind of planet and thus is not necessarily related to other planet characteristics such as  $a$  or  $M$ ; for instance, in the solar system, the Earth is brighter than Uranus and Neptune at low radio frequencies [12]. It is not clear

whether or not the presence of life is incompatible with a large radio emission of the planet.

Most of the observable quantities just mentioned are modulated by a phase factor  $\phi(t)$  with a period  $P$  due to the orbital revolution of the planet. They are related to the intrinsic characteristics of the planetary system by the relations summarized in Table 1.

**Table 1.** Relations between the observable quantities and intrinsic characteristics of the planetary system.

$\Delta\theta$	$= \left(\frac{a}{D}\right) \times \phi(t)$	$= 0.2 \text{ arc sec}$
$\Delta\alpha$	$= \left(\frac{M}{M_\star}\right) \left(\frac{a}{D}\right) \times \phi(t)$	$= 0.6 \text{ } \mu\text{as}$
$\Delta m$	$= A \left(\frac{R}{a}\right)^2 \times \phi(t)$	$= 25 \text{ mag}$
$\Delta R_V$	$= \left(\frac{M \sin i}{M_\star}\right) \left(\frac{GM_\star}{a}\right)^{1/2} \times \phi(t)$	$= 0.1 \text{ m s}^{-1}$
$\Delta T$	$= \left(\frac{a}{c}\right) \left(\frac{M}{M_\star}\right)$	$= 3 \text{ msec}$
$\eta$	$= \left(\frac{R}{R_\star}\right)^2$	$= 10^{-4} \text{ mag}$
$D_{occ}$	$= \left(\frac{P}{\pi}\right) \left(\frac{R_\star}{a}\right)$	$= 15 \text{ hrs}$
$DT$	$= \left(\frac{a}{c}\right) \times \phi(t)$	$= 8 \text{ min}$
$A_G$	$\leq 4 \left(\frac{\sqrt{GMD/c^2}}{R_\star}\right)$	$\leq 1 \text{ mag} \quad (D = 1 \text{ kpc})$
$T_G$	$\approx 4\sqrt{GMD/c^2}/V$	$\approx 4 \text{ hrs} \quad (V = 100 \text{ km s}^{-1})$

The numbers in the right column are for an Earth-sized planet with an albedo 1 at  $a = 1 \text{ AU}$  from its parent star with 1 solar mass at  $5 \text{ pc}$  from the Sun when the phase factor  $\phi(t)$  is equal to 1. For other planetary systems, these numbers scale in an obvious way with the planet and star parameters. They must be compared with the present or forthcoming performances of the instrumentation. We can use this comparison by classifying the methods

of detection according to whether they are adapted to inner planets, outer planets or all planets. The result is shown in the Tables 2 and 3 . The third column gives the physical parameters which can be derived from the observed quantites. The fourth column mentions the astrophysical artefacts which, independently of any systematic *instrumental* error, can mimic, at least before more extensive investigations, the presence of a planet.

The most common methods, namely imaging, astrometry and accelerometry, listed in Table 2, are in fact sensitive only to the presence of outer or giant planets (as far as current searches and sufficiently close to completion projects are concerned). There are naturally ambitious projects to detect Earth-like inner planets with these methods (see for instance [1]) but they have no chance to become operational before at least a couple of decades.

**Table 2.** Detection methods suited only for outer or giant planets.

Method	Observables	Accessible parameters	Physical artefacts
imaging	$\Delta\theta, \Delta m, P$	$AR^2, a, i,$	
astrometry (optical)	$\Delta\alpha, P, i$	$M, a, i$	
astrometry (radio)	$\Delta\alpha, P, i$	$M, a, i$	activity (radio)
accelerometry	$\Delta V_R, P$	$M\sin i, a$	chromospheric activity ?

As for the methods valid for all planets, the most efficient is the timing method. Unfortunately it is only valid for pulsars and is thus helpless for main sequence stars. The gravitational amplification method has the disadvantage that it can reveal the presence of a planet only once (during the single transit due to the proper motion of its parent star) and does not allow by itself for subsequent observations of a detected planet; but in very extensive surveys this method could provide statistical informations on the number of planetary systems.

**Table 3.** Detection methods suited for all planets.

Method	Observables	Accessible parameters	Physical artefacts
radio emission	$F_R, P ?$	$F_R, a ?$	other sources ?
IR excess	$F_{IR}, \lambda_{max}$	$R, a$	circumstel. ring
occultations	$\eta, D_{occ}, P$	$R, a, C[21], i$	
gravitat. amplif.	$A_G, \Delta T$	$M, a_{min} ?$	
timing	$\Delta t, P$	$M \sin i, a$	

The occultation method is finally the only one which can detect inner planets around main sequence stars in the near future and can give some of their characteristics ( $R, a, i$ ); it could even subsequently be used to study the planet atmospheric composition C [21].

### 3. What is effectively done around the world.

There are many projects and programs for the detection of extrasolar planets. Most of them are under development. Some of them have already started. Since we are concerned only in the detection of habitable planets, excluding therefore the outer or giant planets, I will restrict myself in the current efforts in the later case. They are listed in Table 4.

#### 3.1. IDEAS, PROJECTS AND DEVELOPMENTS.

##### 3.1.1. Occultations

It is worth to give some more details about the occultation method since it is the only one by which we can hope to detect habitable planets and measure some of their characteristics in a near future. There are two type of projects. In the space projects [4, 24], the aim is to monitor photometrically thousands of G-stars to search for inner planets. From the ground, because the photometric precision is then only  $\approx 10^{-3}$ , the detection of terrestrial planets is possible only for dwarf (dM) stars [20], for which the transit depth is  $10^{-3}$ . One can increase the efficiency of a random search by choosing stars

whose axis has been predetermined by the comparison of its rotation period, given by  $V_{rot}R_*$ , and its projected rotation velocity  $V_{rot}\sin i$  [10].

The method finds some improvements when the target star is an eclipsing binary. There are then several favourable characteristics:

- the main advantage is that the chances for correct orientation of the planet orbit are close to 100% [19]. This advantage is strengthened by the precession, with a period  $P_{pr} = 16 \cdot P / 3(a/a_{sep})^2$ , of the planet orbit around the binary [22]<sup>1</sup>: it forces an occultation to occur in any case at least once per half precession period.

- furthermore the binary nature of the central star gives a very characteristic shape to the occultation curve: there is not only a double occultation [19], but it consists of a longer and a shorter occultation since the motion of the planet is in the same direction as the star for one of the components and in the opposite direction for the other one [19]; in addition the ephemerides of the second occultation can be predicted with precision from the first one since the orbital motion of the binary is completely known. This makes a double occultation difficult to be confused with any artefact.

### 3.1.2. *Other methods*

The Table 4 does not include the timing searches because there is no timing program specifically aimed for planet detection. Almost every timing campaign on pulsars has the potential to detect planets.

On the other hand I should also mention the spectroscopic search, although no group has specific plans to search for terrestrial planets with this method. Indeed, while a terrestrial planet gives only a reflex velocity of 0.1 m/s for a solar-type star, this velocity is 0.5 m/s for an habitable planet orbiting a dM star; with a precision of 1 m/s as it is envisaged today on a  $m_V = 10$  star [8], it is not hopeless to detect Earth-like planets for these stars with a 10-m class telescope. Let me remark that for dM stars terrestrial planets have orbital periods of the order of weeks and not of years as for Jupiters around suns; this should render the detection easier. As for the habitability of planets around dM stars, it has first been argued that the tidal locking of the planet (which is very close to the star) forbids the presence of liquid water. But 3-D atmospheric circulation may prevent the water evaporation. In addition the internal friction due to tidal forces can be an extra source of heating.

The lensing method could marginally detect Earth-like planets, but it has two disadvantages: 1/ it detects the presence of a given planet only once, as a single event who will never happen again; 2/ it offers no possibility to measure the individual characteristics of the planet, such as mass, inclination of the orbit or distance to the star; it only gives a statistical

<sup>1</sup> $a_{sep}$  being the separation of the binary



distribution of a combination of the mass and the distance to the star projected onto the sky.

**Table 4.** Future projects.

Method	Group	Descript.	Status
imaging	Angel[1]	ground adapt. opt. > 6 meters	design only
	Angel [2]	space 16 m interferom.	design
accelerometry	Connes	laser calibr., $\sigma V_R = 1$ m/s	tests
occultations	FRESIP [?]	dedicated satellite.	NASA proposal
	STARS	satellite dedicated to stellar sismology	ESA proposal
radio emission	Paris- Kharkov [27]	direct radio emissions	tests

### 3.2. CURRENT OBSERVATIONS.

Since a few years an effective searches of extrasolar planets with With the occultation method has started in the frame of the ‘TEP’ (Transists of Extrasolar Planets) network of mutlisite observations [9]. This network currently concentrates on eclipsing pairs of dwarf cool stars (dM stars), for which the depth of the transit due to a terrestrial planet is sufficient to be detectable from the ground [23].

### 3.3. WHAT HAS BEEN FOUND

It is worth mentioning here all the extra-solar planets that have been detected as of January 1996.

**Table 6.** Detected extra-solar planets

Star	$M \times \sin i$	distance to star (AU)	Method	Ref.
PSR 1257+12	0.15 ( $M_{\oplus}$ )	0.19	Timing	[26] xxx
	3.4	0.36		
	2.8	0.47		
51 Pegasus	0.47 $M_{Jup}$	0.05	Acceler.	[17]
47 Ursa Major	2.8 $M_{Jup}$	$\simeq 2$	Acceler.	[6]
70 Virginis	6.4 $M_{Jup}$	0.5	Acceler.	[16]

In the above list, no one is a good candidate for being an habitable planet. If the temperature of PSR1257 were  $10^6$  K, the planet temperature could be around 300 K, but a pulsar is probably an hostile environment for life. The distance of the companion of 70 Vir to its parent star is such that its temperature is  $80^\circ$  C, compatible with the existence of liquid water. But the object is more likely to be a tiny star formed by condensation of a gas cloud, and thus to be completely gaseous: the reason for that is the rather high eccentricity of its orbit. A planet formed by accretion of small bodies would have a circular orbit since the trajectories of planetesimals in a protoplanetary disk are circularised by random collisions. There is nevertheless one chance left for the existence of liquid water in this system: the Jupiter-like companion may well have an Earth-like satellite, just as our Jupiter has solid satellites such as Io or Ganymede. It therefore deserves the most attention of astronomers in a near future.

### 3.3.1. Search for $O_2$ and $O_3$

The final goal of detecting habitable planets is to detect signatures of life. One very promising way is the detection of molecular abundances, compatible only with very out of equilibrium chemical reactions, similar to the high abundance of  $O_2$  in the Earth atmosphere due to the chlorophyllian photosynthesis [14]. It has been suggested to search, by analogy, for  $O_2$  in the optical A band at 760 nm [18] or for  $O_3$  at  $9.6 \mu\text{m}$  [5].

The  $O_2$  band in the visible can be searched for either by spectro-imaging of the planet or by pure spectroscopy during a planetary transit [21]. In the first case a spatial mission would be necessary; in the second case it is worth to investigate whether the observations could be made from the ground with a sufficiently large optical reflector (as no high angular resolution is necessary for spectroscopy).

In the case of the  $O_3$  band at  $9.6\ \mu\text{m}$ , a satellised platform is required, to prevent absorption by the Earth's atmosphere [1]. A more careful investigation, like for instance the DARWIN project submitted to the European Space Agency [13], shows that it is even necessary to go at 3.5 AU or more to suppress the IR background of the zodiacal light.

#### 4. Conclusion

The detection of habitable planets around other main sequence stars is still a great astrophysical and instrumental challenge. In the present decade there is an increasing amount of efforts to detect them by several methods. While the search had up to now been unsuccessful because of instrumental limitations, the first discoveries of Jupiter-like planets are an encouragement to planets hunters and makes the search for terrestrial planets more pertinent than ever.

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